

# MAGNETIC FIELD GRADIENT COIL ASSEMBLY AND METHOD OF DESIGNING SAME

## BACKGROUND OF THE INVENTION

### 5 1. Field of the Invention

The present invention relates to a method of designing a magnetic field gradient coil assembly used in a nuclear magnetic resonance (NMR) spectrometer or the like and to a magnetic field gradient coil assembly designed by such a method.

### 10 2. Description of the Related Art

NMR spectrometers have adopted self-shielding magnetic field gradient coils because quickly rising magnetic field gradient pulses are applied to specimens. The designing procedures used heretofore are now summarized by referring to Figs. 1-4. The designing procedures use the target field method as described by R. Tuner in *A Target Field Approach to Optimal Coil Design*, I. Phys. D: Appl. Phys. **19**, L147-L151 (1986) and by P. Mansfield and B. Chapman in *Multishield Active Magnetic Screening of Coil Structures in NMR*, J. Magn. Reso. **72**, pp. 211-223 (1987). In the target field method, the distributions of electric currents flowing through virtual inside and outside coils are calculated. Furthermore, more coils are distributed computationally. In this way, current distributions are approximated.

Fig. 1 is a schematic diagram of an NMR detector in which a self-shielding magnetic field gradient coil is mounted. Fig. 2 is a schematic view illustrating a system of coordinates used for designing and calculations, as well as a coil bobbin. Fig. 3(a) is a schematic view showing an inner coil. Fig. 3(b) is a schematic view showing an outer coil. These inner and outer coils together form a Z-axis magnetic field gradient coil assembly. Fig. 4 is a flowchart illustrating calculational procedures. As shown in Fig. 1, the NMR detector is comprised of a cover 01, the aforementioned inner coil, indicated by numeral 02, the aforementioned outer coil, indicated by numeral 03, and an NMR detection coil 04. This detector has the coil bobbin in which cylinders 51, 52, 53, and 54 are formed, as shown in Fig. 2. These cylinders 51, 52, 53, and 54 are also

referred to as cylinders 1-4, respectively, and have radii of  $r_t$ ,  $r_p$ ,  $r_s$ , and  $r_b$ , respectively. The radius  $r_t$  of cylinder 1 is the radius of a target magnetic field that takes the form of the cylinder 51. The radius  $r_p$  is the radius of the primary, inner coil, or the cylinder 52. The radius  $r_s$  is the radius of the outer screen coil, or the cylinder 53. The radius  $r_p$  is the radius of the boundary defined by the cylinder 54.

As an example, a Z-axis magnetic field gradient coil assembly is designed using the inner and outer coils in such a way that the magnetic field strength at the boundary having the radius  $r_b$  is 0 (self-shielding) and that a target magnetic field strength is obtained at the radius  $r_t$  at which a specimen is placed. A Green function  $G(k)$  used for magnetic field analysis is defined by Eqs. (1)-(6) below.

$$B(z)_{p,r=r_t} = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_p G(k)_{r_p \rightarrow r_t} dk$$

Eq. 1

$$B(z)_{s,r=r_t} = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_s G(k)_{r_s \rightarrow r_t} dk$$

Eq. 2

$$B(z)_{p,r=r_b} = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_p G(k)_{r_p \rightarrow r_b} dk$$

Eq. (3)

$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_s G(k) dk$$

$s, r=r_b$   $r_s \rightarrow r_b$

Eq. (4)

$$j(k)_p, j(k)_s : j(k)_s = \int_{-\infty}^{+\infty} e^{-ikz} J(z) dz$$

Eq. (5)

$$G(k), G(k), G(k), G(k)$$

$r_p \rightarrow r_t$     $r_s \rightarrow r_t$     $r_p \rightarrow r_b$     $r_s \rightarrow r_b$

Esq. (6)

Eq. (1) indicates a magnetic field produced by the inner coil subassembly at the radius  $r_t$ . Eq. (2) indicates a magnetic field by the outer coil subassembly at the radius  $r_t$ . Eq. (3) indicates a magnetic field developed by the inner coil subassembly at the boundary radius  $r_b$  obtained by calculation. Eq. (4) indicates a magnetic field set up by the outer coil subassembly at the boundary radius  $r_b$  obtained by calculation. Eq. (5) defines Fourier components  $j(k)_p$  and  $j(k)_s$  of the current density distributions in the inner and outer coil subassemblies, respectively. Eq. (6) indicates a current-field Green function (response function) in a Fourier space. In this equation,  $r_p \rightarrow r_t$ ,  $r_s \rightarrow r_t$ ,  $r_p \rightarrow r_b$ , and  $r_s \rightarrow r_b$  mean that the inner and outer coils produce magnetic fields at the radii  $r_t$  and  $r_b$ , respectively.

The calculational procedures are next described by referring to the flowchart of Fig. 4. A target magnetic field distribution  $TARGET(z)$  is set. A target value of the magnetic field distribution generated by the coil assembly near the center axis of the cylinder of the detector is set (step S1). The Fourier

components  $target(k)$  of the target magnetic field distribution  $TARGET(z)$  are calculated using Eq. (7) (step S2).

$$target(k) = \int_{-\infty}^{+\infty} e^{-ikz} TARGET(z) dz$$

Eq. (7)

A current-field Green function (response function) adapted for the designed coil assembly is found. Using this Green function and  $target(k)$ , the Fourier components  $j(k)_p$  and  $j(k)_s$  of the distributions of the currents flowing through the virtual inner and outer self-shielding coils are calculated (step S3).

Where the sum of magnetic fields given by the Fourier components of the distributions of the currents flowing through the inner and outer coils at the boundary  $r_b$  is null, shielding conditions are satisfied. Under this state, if the Fourier components  $j(k)_p$  of the distribution of the current flowing through the inner coils is used, the Fourier components  $j(k)_s$  of the distribution of the current flowing through the outer coils is given by Eq. (8).

$$j(k)_s = -j(k)_p \frac{G(k)_{r_p \rightarrow r_b}}{G(k)_{r_s \rightarrow r_b}}$$

Eq. (8)

Accordingly, the Fourier components  $b(k)$  of the magnetic fields produced by the inner and outer coils are given by Eq. (9).

$$b(k) = j(k)_p \underset{r_p \rightarrow r_t}{G(k)} + j(k)_s \underset{r_s \rightarrow r_t}{G(k)} = j(k)_p \left( \underset{r_p \rightarrow r_t}{G(k)} - \frac{\underset{r_s \rightarrow r_t}{r_p \rightarrow r_b} G(k)}{\underset{r_s \rightarrow r_b}{G(k)}} \right)$$

Eq. (9)

- 5 Since  $b(k) = target(k)$ , the Fourier components  $j(k)_p$  and  $j(k)_s$  of the distributions of the currents flowing through the virtual inner and outer coils are respectively given by:

$$j(k)_p = \frac{target(k)}{\left[ \underset{r_p \rightarrow r_t}{G(k)} - \frac{\underset{r_s \rightarrow r_t}{r_p \rightarrow r_b} G(k)}{\underset{r_s \rightarrow r_b}{G(k)}} \right]}$$

Eq. (10)

$$j(k)_s = -j(k)_p \frac{\underset{r_p \rightarrow r_b}{G(k)}}{\underset{r_s \rightarrow r_b}{G(k)}}$$

Eq. (11)

10

15

By inverse-Fourier-transforming the Fourier components  $j(k)_p$  and  $j(k)_s$ , the distributions  $J(z)_p$  and  $J(z)_s$  of the currents flowing through the virtual inner and outer coils are found (step S4). The distributions  $J(z)_p$  and  $J(z)_s$  of the currents flowing through the virtual inner and outer coils are integrated, and the

positions of the coils conforming to the calculated current distributions are determined (step S5).

With the above-described designing procedures, the currents flowing through the inner and outer coils are calculated simultaneously. Therefore, if the results of the calculations of the current distributions are ideal, and if the coils are large, then it is possible to wind the coils exactly. However, as the coils decrease in size, it becomes more difficult to fabricate the coils accurately, that is, it is necessary to wind conductive wire into a bobbin shape (i.e., distributed winding) according to the calculated coil geometry in order to obtain the current distributions found by calculations. Generally, many turns of wire are necessary to conform with the calculated coil geometry. Adjacent turns of wire come too close. Hence, it is difficult to wind the wire completely in accordance with the coil geometry. If lap winding is done, the coil diameter increases, thus varying the calculational conditions. If the number of turns of wire is few, the approximation error becomes large. This deteriorates the performance. To avoid this, the number of turns of wire must be increased, and the spacing between the adjacent turns of wire must be decreased. Thus, the target current distributions must be approximated with high accuracy. This is not a realistic solution.

In the case of a narrow-bore (NB) superconducting magnet (SCM), it is desired to set the inside diameter of the magnetic field gradient coils greater than 50% of the inside diameter of the probe cover. However, this cannot be achieved for the following reason. If the former inside diameter is set greater than 50%, the magnetic field leaking to the outside through the outer coil produces a large amount of eddy currents on the cover, thus reducing the rising speed. To avoid this, it is necessary to increase the number of turns of wire forming the coils and to distribute the turns of wire closely, for improving the accuracy of approximation. This will reduce the leakage of the magnetic field. However, this approach is difficult to accomplish because of coil resistance and restrictions on the mechanical dimensions. Furthermore, electric interference

between a DC magnetic field gradient coil and the detection coil operating at hundreds of megahertz is large, lowering the Q of the detection coil. Consequently, the sensitivity drops. As a countermeasure, it is conceivable that an RF shield is formed inside the magnetic field gradient coil. However, this shield heavily interferes with the detection coil. This also lowers the Q.

### SUMMARY OF THE INVENTION

It is an object of the present invention to provide a magnetic field gradient coil assembly that provides high approximation accuracy, is simple in structure, has a large inside diameter, permits small-sized self-shielding coils to be designed, and responds at a sufficient speed to be used in high-resolution NMR spectrometers. It is another object of the present invention to provide a method of designing this magnetic field gradient coil assembly.

A method of designing a magnetic field gradient coil assembly in accordance with the present invention uses tightly wound inner and outer coils to fabricate the gradient coil assembly. This method starts with setting or resetting the number of the inner coils and the number of turns of each inner coil and optimizing their positions such that a resulting magnetic field strength falls within a tolerable range of a target magnetic field gradient under shielded conditions. Then, the number of the outer coils and the number of turns of each outer coil are set. Thereafter, Fourier components of an electric current distribution necessary for the outer coils are calculated. The positions of the outer coils are optimized to approximate the Fourier components of the current distribution. Magnetic fields leaking from the inner and outer coils, respectively, are calculated. Magnetic field distortions caused by eddy currents produced by the leaking magnetic fields are calculated. Finally, the number of the outer coils and the number of turns of each outer coil are reset if the magnetic field distortions are outside the tolerable range.

In one feature of the present invention, the aforementioned step of setting or resetting the number of the inner coils and optimizing their positions

such that a resulting magnetic field strength falls within a tolerable range of a target magnetic field gradient under shielded conditions uses a Green function.

In another feature of the present invention, the aforementioned step of calculating Fourier components of an electric current distribution  
5 necessary for the outer coils uses a Green function.

In a further feature of the present invention, the aforementioned step of optimizing the positions of the outer coils to approximate the Fourier components of the current distribution performs the approximation using a small number of tightly wound coils.

10 In a still further feature of the present invention, the aforementioned step of calculating magnetic fields leaking from the inner and outer coils, respectively, and the step of calculating magnetic field distortions caused by eddy currents produced by the leaking magnetic fields use a Green function.

15 In a yet further feature of the present invention, the aforementioned step of resetting the number of the outer coils and the number of turns of each outer coil if the magnetic field distortions are outside the tolerable range, the step of calculating Fourier components of an electric current distribution necessary for the outer coils, the step of optimizing the positions of  
20 the outer coils to approximate the Fourier components of the current distribution by the outer coils, the step of calculating magnetic fields leaking from the inner and outer coils, respectively, and the step of calculating magnetic field distortions caused by eddy currents produced by the leaking magnetic fields are repeatedly carried out to determine optimum conditions for the outer coils by  
25 trial and error.

Furthermore, the present invention provides a magnetic field gradient coil assembly having tightly wound inner and outer coils, the magnetic field gradient coil assembly having been designed by a method starting with  
30 setting or resetting the number of the inner coils and the number of turns of each inner coil and optimizing their positions such that a resulting magnetic field



strength falls within a tolerable range of a target magnetic field gradient under shielded conditions. Then, the number of the outer coils and the number of turns of each outer coil are set. Thereafter, Fourier components of an electric current distribution necessary for the outer coils are calculated. The positions of the outer coils are optimized to approximate the Fourier components of the current distribution. Magnetic fields leaking from the inner and outer coils, respectively, are calculated. Magnetic field distortions caused by eddy currents produced by the leaking magnetic fields are calculated. Finally, the number of the outer coils and the number of turns of each outer coil are reset if the magnetic field distortions are outside the tolerable range.

In one aspect of this method, the aforementioned step of setting or resetting the number of the inner coils and optimizing their positions such that a resulting magnetic field strength falls within a tolerable range of a target magnetic field gradient under shielded conditions uses a Green function.

In another aspect of this method, the aforementioned step of calculating Fourier components of an electric current distribution necessary for the outer coils uses a Green function.

In a further aspect of this method, the aforementioned step of optimizing the positions of the outer coils to approximate the Fourier components of the current distribution performs the approximation using a small number of tightly wound coils.

In a still other aspect of this method, the aforementioned step of calculating magnetic fields leaking from the inner and outer coils, respectively, and the step of calculating magnetic field distortions caused by eddy currents produced by the leaking magnetic fields use a Green function.

In an additional aspect of this method, the aforementioned step of resetting the number of the outer coils and the number of turns of each outer coil if the magnetic field distortions are outside the tolerable range, the step of calculating Fourier components of an electric current distribution necessary for the outer coils, the step of optimizing the positions of the outer coils to

approximate the Fourier components of the current distribution, the step of calculating magnetic fields leaking from the inner and outer coils, respectively, and the step of calculating magnetic field distortions caused by eddy currents produced by the leaking magnetic fields are repeatedly carried out to determine  
5 optimum conditions for the outer coils by trial and error.

Other objects and features of the present invention will appear in the course of the description thereof, which follows.

### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a conceptual view of a detector in which a self-shielding  
10 magnetic field coil assembly is mounted;

Fig. 2 is a side elevation of a coil bobbin, and in which a system of coordinates used for designing and calculations is also shown;

Figs. 3(a) and 3(b) are schematic views of an inner coil and an  
outer coil;

Fig. 4 is a flowchart illustrating calculational procedures used in  
the prior art method;

Figs. 5(a) and 5(b) are views illustrating the structure of an inner  
coil subassembly in accordance with an embodiment of the present invention;

Figs. 6(a) and 6(b) are views illustrating the structure of an outer  
coil subassembly in accordance with an embodiment of the present invention;

Fig. 7 is a flowchart illustrating calculational procedures used in  
the present invention;

Fig. 8 is a graph showing Green function values in an example of  
design; and

Fig. 9 is a graph showing Fourier components of magnetic fields at  
a boundary in an example of design.

### DESCRIPTION OF THE PREFERRED EMBODIMENTS

The preferred embodiments of the invention are hereinafter described. In the following description, the NMR detector of the structure  
30 described in connection with Fig. 1 and the system of coordinates and the coil

bobbin used for designing and calculations already described in conjunction with Fig. 2 are also used. Accordingly, in the same way as in the prior art structure described previously, the detector of interest has a coil bobbin formed by cylinders 51, 52, 53, and 54, which are also referred to as cylinder 1, cylinder 2, cylinder 3, and cylinder 4, respectively. These cylinders 51, 52, 53, and 54 have radii of  $r_t$ ,  $r_p$ ,  $r_s$ , and  $r_b$ , respectively. The radius  $r_t$  of cylinder 1 is the radius of a target magnetic field taking the form of the cylinder 51. The radius  $r_p$  is the radius of the primary, inner coil, or the cylinder 52. The radius  $r_s$  is the radius of the outer screen coil, or the cylinder 53. The radius  $r_b$  is the radius of the boundary defined by the cylinder 54. An example of design of a Z-axis magnetic field gradient coil assembly is now taken. We assume that  $r_t = 0$ ,  $r_p = 1.0$ ,  $r_s = 1.33$ , and  $r_b = 1.5$ .

Figs. 5(a) and 5(b) show the structure of an inner coil subassembly in accordance with the present invention. Figs. 6(a) and 6(b) show the structure of an outer coil subassembly in accordance with the present invention. In the present invention, tightly wound coils having a given width are used. Fig. 5(a) shows the structure of the inner coil subassembly. Fig. 5(b) shows the distribution of surface current densities, and in which the clockwise direction as viewed from the + side of the Z-axis is indicated by +. Fig. 6(a) shows the structure of the outer coil subassembly. Fig. 6(b) shows the distribution of surface current densities.

The inner coil subassembly consists of wire coils 61 and 62. Each of the tightly wound coils spans a width of  $w_n^p$ . Their centers are located at  $d_n^p$  ( $n = 1$ ). The outer coil subassembly consists of a first set of coils consisting of four tightly wound coils 71-1, 71-2, 71-3, and 71-4 and a second set of coils consisting of four tightly wound coils 72-1, 72-2, 72-3, and 72-4. Each of the tightly wound coils spans a width of  $w_n^s$ . The centers are located at  $d_n^s$  ( $n = 1, 2, 3, 4$ ). Fig. 7 is a flowchart illustrating the calculational procedures in the present invention.

The Green function  $G(k)$  for use in magnetic field analysis employs Eqs. (1)-(6) intact, the Eqs. (1)-(6) being used in the description of the prior art technique. Green function values in this example of design are given in Fig. 8.

5 With respect to a Green function for calculation of eddy currents, let  $r_{b1}$  be the radius of the inner wall of the probe. Let  $r_{b2}$  be the radius of a calculated boundary of eddy currents produced on its circumference. Also, it is assumed that  $r_p < r_s < r_{b1} < r_{b2}$ . The Green function is defined as given by Eqs. (12)-(15):

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$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_p G(k) dk$$

Eq. (12)

$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_s G(k) dk$$

Eq. (13)

$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_{b1} G(k) dk$$

Eq. (14)

$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_{b1} G(k) dk$$

Eq. (15)

where  $j(k)_{b1}$  are the Fourier components of eddy currents produced on the inner wall of the probe. Eq. (12) indicates the magnetic field produced by the inner coil subassembly at the radius  $r_{b2}$ . Eq. (13) indicates the magnetic field produced by the outer coil subassembly at the radius  $r_{b2}$ . Eq. (14) indicates the magnetic field produced at the radius  $r_{b2}$  by the eddy currents produced on the inner wall of the probe at the radius  $r_{b1}$ . Eq. (15) indicates the magnetic field produced at the radius  $r_1$  by the eddy currents produced at the radius  $r_{b1}$  on the inner wall of the probe. The calculational procedures are next described by referring to the flowchart of Fig. 7.

The number of the tightly wound coils forming the inner coil subassembly and the number of turns of each inner coil are determined, taking account of the actual fabrication. At this time, the width  $w_n^p$  that each tightly wound coil spans is determined (step S11). Using a Green function, the positions of the inner coils under the shielded condition are optimized, that is, distortion terms  $z^3$ ,  $z^5$ , etc. are minimized. It is assumed that there is a perfect outer coil subassembly, thus completely shielding the inner coils (step S12).

The distribution in the current flowing through each inner coil is given by Eq. (16).

$$J(z)_p = \frac{I}{D^p} \sum_{n=1}^{N_p} \left[ \frac{-H(z + d_n^p - W_n^p/2) \left( 1 - H(z + d_n^p - W_n^p/2) \right)}{+ H(z - d_n^p + W_n^p/2) \left( 1 - H(z - d_n^p + W_n^p/2) \right)} \right]$$

Eq. (16)

where  $D^p$  is the diameter of the wire forming each inner coil,  $j(z)_p$  is the current distribution function,  $H(z)$  is a Heaviside function, and  $N_p$  is the number of turns of each tightly wound coil. Because tightly wound coils are used, the current

distribution takes the form of pulses and is represented as given above. Since there are two tightly wound coils arranged symmetrically about the center, the relation  $N_p = 1$  holds. The center position  $d_n^p$  ( $n = 1$ ) is a variable to be optimized.

Because the current distribution is given by an odd function with respect to the Z-axis (Eq. (17)), the Fourier functions of the current distribution are given by:

$$j(k)_p =$$

$$\int_{-\infty}^{+\infty} e^{-ikz} J(z)_p dz = \frac{I}{D^p} \sum_{n=1}^{N_p} \frac{2i}{k} \left\{ -\cos \left( k \left( d_n^p - W_n^p / 2 \right) \right) + \cos \left( k \left( d_n^p + W_n^p / 2 \right) \right) \right\}$$

Eq. (17)

Outside the outer coil subassembly, the magnetic field strength must be 0 at the calculated boundary  $r_b$ , i.e., the magnetic fields must cancel out completely. For this purpose, the distribution of the current flowing through the outer coils is given by:

$$B_{p,r=r_b}(z) = - B_{s,r=r_b}(z)$$

Eq. (18)

If this condition is expressed by current-density Fourier components, the Fourier components of the distribution of the density of the current flowing through the outer coils are given as follows, using a Green 1

function and  $j(k)_p$ .

$$j(k)_s = -j(k)_p \frac{G(k)_{r_p \rightarrow r_b}}{G(k)_{r_s \rightarrow r_b}}$$

Eq. (19)

5 When the outer coil subassembly is shielding the magnetic field, the strengths of the magnetic fields produced by the inner and outer coil subassemblies in the center are respectively given by Eqs. (20) and (21).

$$B(z)_{p, r=r_t} = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_p \frac{screen}{G(k)_{r_p \rightarrow r_t}} dk$$

10

Eq. 20

$$screen G(k)_{r_p \rightarrow r_t} = G(k)_{r_p \rightarrow r_t} - \frac{G(k)_{r_p \rightarrow r_b} G(k)_{r_s \rightarrow r_t}}{G(k)_{rs \rightarrow rb}}$$

15

Eq. (21)

Using the Green function of Eq. (21), the strength of the magnetic field produced by the inner coil subassembly at the target position  $r_t$  can be

expanded with respect to  $Z$  as given by Eq. (22)

$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k) G(k) dk$$

$r_p \rightarrow r_t$

Eq. 22

$$\begin{aligned} &= \frac{\mu}{2\pi} \int_0^{+\infty} \left\{ 1 + (ikz) + \frac{1}{2!} (ikz)^2 + \frac{1}{3!} (ikz)^3 + \dots \right\} \\ &\left[ \frac{I}{D^p} \sum_{n=1}^{N_p} \frac{2i}{k} \left\{ -\cos(k(d_n^p - w_n^p/2)) + \cos(k(d_n^p + w_n^p/2)) \right\} \right] G(k) dk \Bigg|_{r_p \rightarrow r_t}^{screen} \\ &= \frac{I}{D^p} \frac{2\mu}{\pi} \int_0^{+\infty} \left\{ z - \frac{1}{3!} k^2 z^3 + \frac{1}{5!} k^4 z^5 \dots \right\} \\ &\left[ \sum_{n=1}^{N_p} \left\{ \cos(k(d_n^p - w_n^p/2)) - \cos(k(d_n^p + w_n^p/2)) \right\} \right] G(k) dk \Bigg|_{r_p \rightarrow r_t}^{screen} \\ &= I \frac{2\mu}{\pi} \{ Q_1(d, w) \cdot z + Q_3(d, w) \cdot z^3 + Q_5(d, w) \cdot z^5 \dots \} \end{aligned}$$

Since the current distribution is an odd function, there are no even terms. The first-order term (magnetic field gradient strength)  $Q_1$  and the third-order term (distortion)  $Q_3$  of the magnetic field components produced by the coil subassembly are given by Eqs. (23) and (24), respectively. Here,  $d_n^p$  that minimizes the magnetic field strength  $Q_3$  is found.



$$Q_1(d_n^p, w_n^p) = \frac{2\mu}{\pi} \sum_{n=1}^{Np} \int_0^{+\infty} \left\{ \cos(k(d_n^p - w_n^p/2)) - \cos(k(d_n^p + w_n^p/2)) \right\} \overset{screen}{G(k)dk} \Big|_{r_p \rightarrow r_t}$$

Eq. (23)

$$Q_3(d_n^p, w_n^p) = -\frac{2\mu}{3!\pi} \sum_{n=1}^{Np} \int_0^{+\infty} k^2 \left\{ \cos(k(d_n^p - w_n^p/2)) - \cos(k(d_n^p + w_n^p/2)) \right\} \overset{screen}{G(k)dk} \Big|_{r_p \rightarrow r_t}$$

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(24)

The optimum values in the example of design are  $d_1^p = 0.89$  and  $w_1^p = 0.63$ .

If the magnetic field distortion is not within the tolerable range, the structure of the inner coil subassembly is reset. Then, the designer returns to the step S12, where the sequence of operations is repeated (steps S13 and S14). If the magnetic field distortion is within the tolerable range, the number of tightly wound coils forming the outer coil subassembly and the number of turns of each coil are set (step S15). Thus, the value of the width  $w_n^p$  that each tightly wound coil spans is determined (step S16).

15

Since the Fourier components of the current distribution that the outer coil subassembly must achieve satisfy the condition that the magnetic field strength at the calculated boundary  $r_b$  is 0, the Fourier components are given by:

$$j(k)_s = -j(k) \frac{r_p \rightarrow r_b}{G(k)} \Big|_{r_s \rightarrow r_b}$$

Eq. (25)

The Fourier components  $j(k)_s$  of the current distribution are approximated by optimizing the positions of the coils of the outer coil subassembly (step S17). With the prior art designing method, the Fourier components  $j(k)_s$  are inverse-Fourier-transformed to find the current distribution, and many turns of conductive wire are distributed for approximation. In the present invention, the current density distribution Fourier components  $j(k)_s$  that the outer coil subassembly must achieve are approximated by a small number of tightly wound outer coils preset in step S15, as described below.

As shown in Fig. 8, the response function exponentially decays in a region where  $k$  is large. Therefore, in this example of designing in accordance with the present invention, it can be seen that approximation in a low range with approximately  $k = 1$  to 1.5 suffices. The Fourier components  $j(k)_s$  are given by:

15

$$\begin{aligned}
 j(k)_s &= -j(k)_p \frac{G(k)_{r_p \rightarrow r_b}}{G(k)_{r_s \rightarrow r_b}} \\
 &= -\frac{I}{D^s} \sum_{n=1}^{N_s} \frac{2i}{k} \left\{ -\cos \left( k \left( d_n^s - w_n^s / 2 \right) \right) + \cos \left( k \left( d_n^s + w_n^s / 2 \right) \right) \right\} + error(k)
 \end{aligned}$$

Eq. (26)

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where  $D^s$  is the pitch of the turns of each outer coil,  $d_n^s$  gives the positions of the upper and lower coils,  $w_n^s$  is the width that each tightly wound coil spans, and  $N_s$  is the number of the tightly wound coils. In this example of design,  $N_s = 4$ .

Optimization is performed with numerical calculations to minimize error(k) in a low range of k. Calculations show that the optimum values are:

$$d_1^s = 0.41 \quad w_1^s = 0.13$$

$$d_2^s = 0.41 \quad w_2^s = 0.20$$

$$5 \quad d_3^s = 1.12 \quad w_3^s = 0.26$$

$$d_4^s = 1.73 \quad w_4^s = 0.066$$

Fig. 9 is a diagram illustrating the Fourier components of magnetic fields on the boundary in the example of design. The magnetic fields are developed respectively by a primary (inner) coil, a screen (outer) coil, a combination of the primary coil and the screen coil, and the screen coils (n = 1, 2, 3, and 4, respectively). The Fourier components of the magnetic fields produced by the inner and outer coils are given by Eqs. (27) and (28), respectively.

$$b(k)_{primary} = j(k)_p \underset{r_p \rightarrow r_b}{G(k)}$$

Eq. (27)

$$b(k)_{screen} = j(k)_s \underset{r_s \rightarrow r_b}{G(k)}$$

Eq. (28)

Using a Green function, magnetic fields leaking from the inner and outer coil subassemblies are calculated. Also, magnetic field distortions caused by eddy currents produced by the leaking fields are calculated (step S18).

It is assumed that the inner wall of the probe through which eddy current flows has an ideal radius  $r_{b1}$ . The condition that generation of eddy current prevents magnetic field from leaking outside the probe is replaced by an ideal coil. Then, calculations are performed. The Fourier components of the current at the radius  $r_{b1}$  are given by Eq. (29). The magnetic field at the radius  $r_t$  is given by Eq. (30).

$$j(k)_{b1} = - \left[ \frac{I}{D^p} \sum_{n=1}^{Np} \frac{2i}{k} \left\{ -\cos(k(d_n^p - w_n^p/2)) + \cos(k(d_n^p + w_n^p/2)) \right\} \right] \frac{1}{\frac{G(k)}{r_{b1} \rightarrow r_{b2}}}$$

Eq. (29)

$$B(z) = \frac{\mu}{2\pi} \int_{-\infty}^{+\infty} e^{ikz} j(k)_{b1} G(k) dk \quad r_{b1} \rightarrow r_i$$

Eq. (30)

By performing this inverse Fourier transformation, magnetic field distortion due to eddy current is obtained (steps S19 and S20).

If the magnetic field distortion is minimum or within a tolerable range, then the designing is ended. If it is not within the tolerable range, the number of the tightly wound outer coils or the number of turns of each outer coil is reset, and then the step S16 and the subsequent steps are repeated.

In the example of designing described above, the number of the tightly wound inner coils is two. Of course, the invention is not limited to this structure. The linearity can be improved by fabricating the inner coil subassembly from plural pairs of coils. Furthermore, the number of the outer coils may be so modified that the magnetic field distortion falls within the tolerable range. In addition, the theory of the invention can also be applied to designing of X- and Y-axis magnetic field gradient coils, such as saddle coils, as well as Z-axis magnetic field gradient coils. Fingerprint coils designed conventionally can be approximated by plural saddle coils. Furthermore, in the above-described prior art design, the coil assembly consists of a double coil made up of an inner coil subassembly and an outer coil subassembly. The coil assembly may be made of a triple coil or more complex coil structure.

As described thus far, in the present invention, calculation of approximation of an electric current is performed using Fourier components. Therefore, a self-shielding coil of simple structure can be designed. Since the approximation accuracy is high, a coil having a large inside diameter and a simple structure can be easily designed. Furthermore, a small-sized coil can be designed.

Additionally, a realistic coil geometry is established as an initial model and calculated. Consequently, the finally obtained coil geometry can be easily accomplished.

Moreover, individual coils of the inner and outer coil subassemblies are separately calculated. Therefore, a large number of degrees of freedom are given in designing the geometry of each coil. Since the conditions are so set that the magnetic field distortion due to eddy currents becomes null, a coil assembly having good response can be designed.

Further, in the present invention, electric currents are supplied to the inner and outer coils simultaneously as in the conventional designing method to set up magnetic fields. The outer coils do not completely shield the magnetic field. Therefore, eddy currents are produced on the detector cover. However, the eddy currents cancel out the magnetic fields. Also, the amount of magnetic field distortion is small. In addition, the magnetic field energy is small. Consequently, the eddy currents decay quickly and hence magnetic field response similar to the response obtained by the conventional design can be obtained. Therefore, the novel design can be used for high-resolution NMR measurements. Moreover, the inside diameter of the magnetic field gradient coil assembly can be set large. The inside diameter of the inner coil subassembly can be set greater than 70% of the inside diameter of the cover. Since interference with the detection coil does not occur, the sensitivity is prevented from deteriorating. In addition, a heat-insulating tube or an RF shield can be mounted inside without impairing the sensitivity.

Having thus described my invention with the detail and particularity required by the Patent Laws, what is desired protected by Letters Patent is set forth in the following claims.